Engineering Case Library

ECL 241

INTERMEDIATE AIR RECEIVER FRACTURE

An apparently standard air vessel burst and tore from its mounting. This case describes circumstances of use of this pressure vessel, and some investigations on the possible causes of failure.

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INTERMEDIATE AIR RECEIVER FRACTURE - PART A

An investigation into a potentially fatal accident, traced to its probable causes by the author, W. Ernst Eder, The University of Calgary.

INTRODUCTION

In June 1975 a burst air receiver was delivered to me by Mr. T. Smith, Energy Resources Conservation Board of Alberta, who asked me to try to trace the cause of failure and recommend on possible procedure to avoid similar failures the future.

The air receiver formed part of the equipment of a front-end loading machine used in open-cast mining. These are large wheeled machines that scoop loose dirt and rocks (overburden) or coal from a pile deposited by the breakers. Two articulated arms push the material up a ramp, and onto the front end of a conveyor belt. The direction of motion (steering) and angle attitude of the ramp are changed by air-powered ram cylinders.

According to the information given verbally by Mr. Smith, this air receiver was installed in the front-end loader by the operating company, after some modifications had been made to an otherwise standard pressure vessel by them or by their agents. Its purpose was to introduce a pool of liquid into the compressed air system in order to dry (prevent freezing at the exhaust ports) the air by leading it across the surface of this pool, and to be able to replenish the pool without reduction of pressure in the main storage receiver. Suitable shut-off valves were installed to isolate the user sections (rams, air

motors, etc.) from the main storage receiver, drop pressure in the user parts, introduce the liquid into the intermediate receiver, and restore pressure in the user sections of the compressed air system.

On a routine basis, two alternative liquids were intended to be used to prevent freezing of the air exhausts. One of these was a commercial product, the other was de-natured alcohol (methylated spirits), a volatile liquid that can absorb a large amount of water into solution, both in liquid and in vapour form. The resulting water/alcohol solution shows a freezing point below that of water alone, depending on the proportion of water in solution (pure ethyl alcohol freezes at $-115^{\circ}C$, $-174^{\circ}F$). The machine units were also provided with small quantities of ether to assist in starting the main power unit engines.

The air receiver as it burst caused some incidental damage to the front-end loader, but luckily no injuries or deaths resulted at that time. After the incident, the loader operator was reluctant to give information on any of his procedures. His only useful statement was that he heard some rattling from the machine housing and thought that the air receiver may have been loose on its mounting.

PRELIMINARY OBSERVATIONS

The receiver, as delivered by Mr. Smith, is shown in figs. 1, 2 and 3. I mentally reconstructed the pressure vessel, see exhibit 1, although I had no opportunity of checking this against an installed air receiver in other operating front-end loaders. It was a standard pressure vessel to S.A.E. Code J-10 (Air Brake Reservoir Test Code and Inspection Procedure, last revision February 1972), and marked by the manufacturer

"CON-MET PORTLAND, ORE. ISI O-70 SAE CODE J-10 150 PSI MAX W.P." The S.A.E. code specifies tests for maximum deformation under test pressure, leakage test, and corrosion protection test for both inside and outside surfaces.

The rupture followed the line of the longitudinal weld seam, and turned close to the head seams at both ends, see figs. 4, 5 and 6, and exhibit 2. Features of the rupture surface I noted at this point were: a sharp, feathered edge with some thinning reaching back about 1.5 mm (1/16 in.) into the parent metal (see fig. 7); the weld metal was adjacent to the rupture on one side or the other for most of its length; some areas of incomplete penetration of the weld were obvious (see figs. 8 and 9), leaving about half of the thickness of the parent metal visible for about 250 mm (10 in.) of the total vessel length of 610 mm (24 in.); a circumferential rupture progressed at about 150 mm (6 in.) from one end, and reaching around three quarters of the circumference.

As a result of the rupture, the receiver was torn from its mounting, and propelled rocket-like against a structural member or service pipe, causing the scuff marks near an entry plug, figs. 10, 11 and 12. The mounting bolts were apparently not found, and were not available to me.

A brass valve attached to a double-end screwed pipe fitting at one end of the receiver was loosened and rotated during the rupture events. Apparently, no other piping was attached to the valve, which was probably opened by the machine operator to blow down the user sections of the air system, in preparation for replenishing the drying liquid.

The opposite end of the receiver contained two entries (see figs. 13 and 14). One was a boss with a single brass screwed pipe end, which had fractured at the entry in the root of a male thread. The second was a tube entering the vessel, with two steel screwed pipe ends, one entering from inside the vessel, the other from outside, both showing fractures at the entry points. The areas around these entries had been reinforced by welded plates, the welds having been made by electric arc hand welding. Slag was not cleaned off, weld spatter appeared on the parent metal and on the reinforcements, and the corrosion protection paint on the inside surface of the vessel had been burned off. The head seams on the air receiver, close to the longitudinal seam of the body, had been repair-welded, leaving an unpainted area visible on the inside (see figs. 6 and 13).

The air receiver was comparatively clean, but judging from the torn and twisted metal, I am glad that I was not in its way!

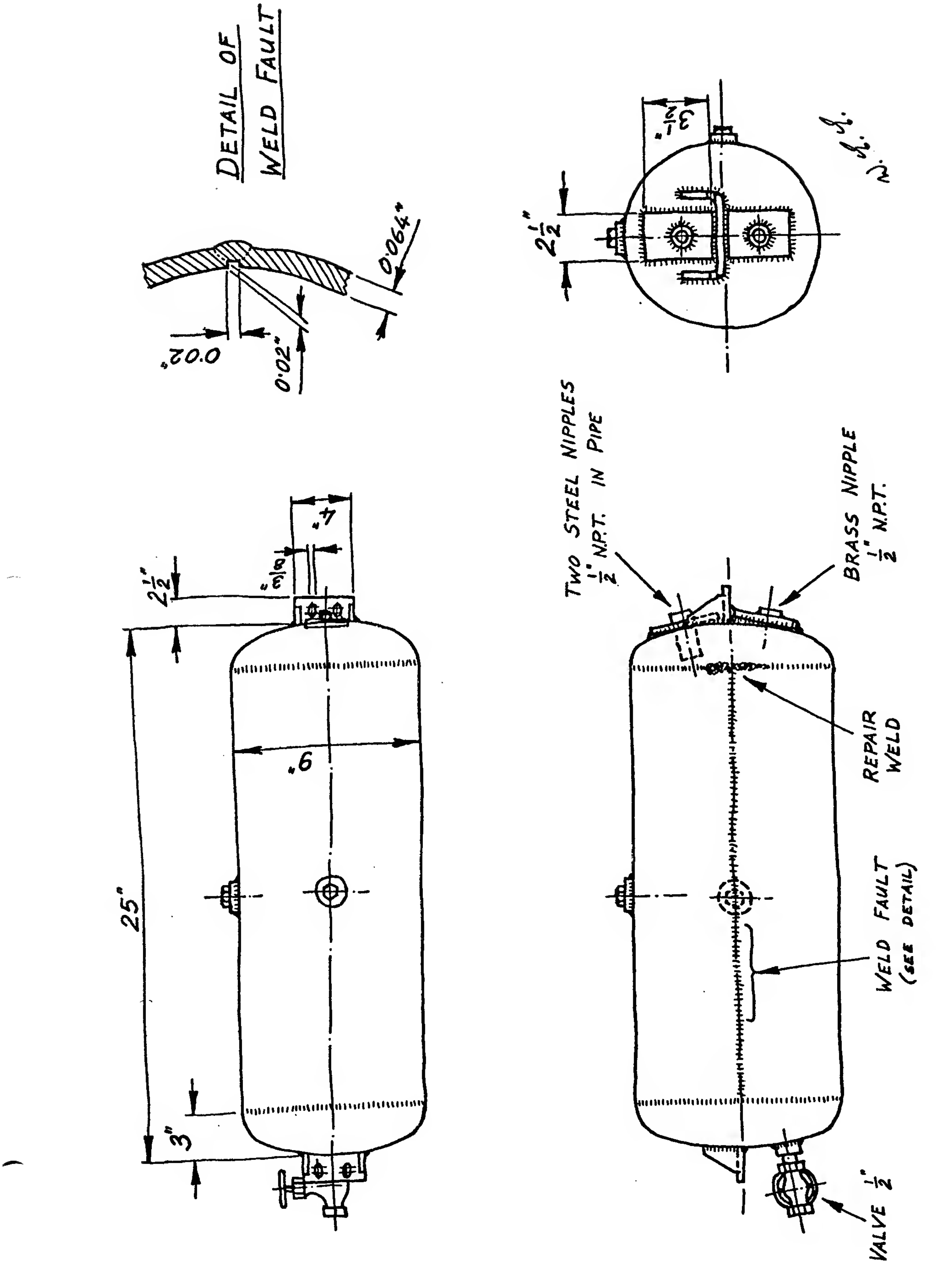

Exhibit 1 - INTERMEDIATE AIR RECEIVER, E.R.C.B. - DIMENSIONS

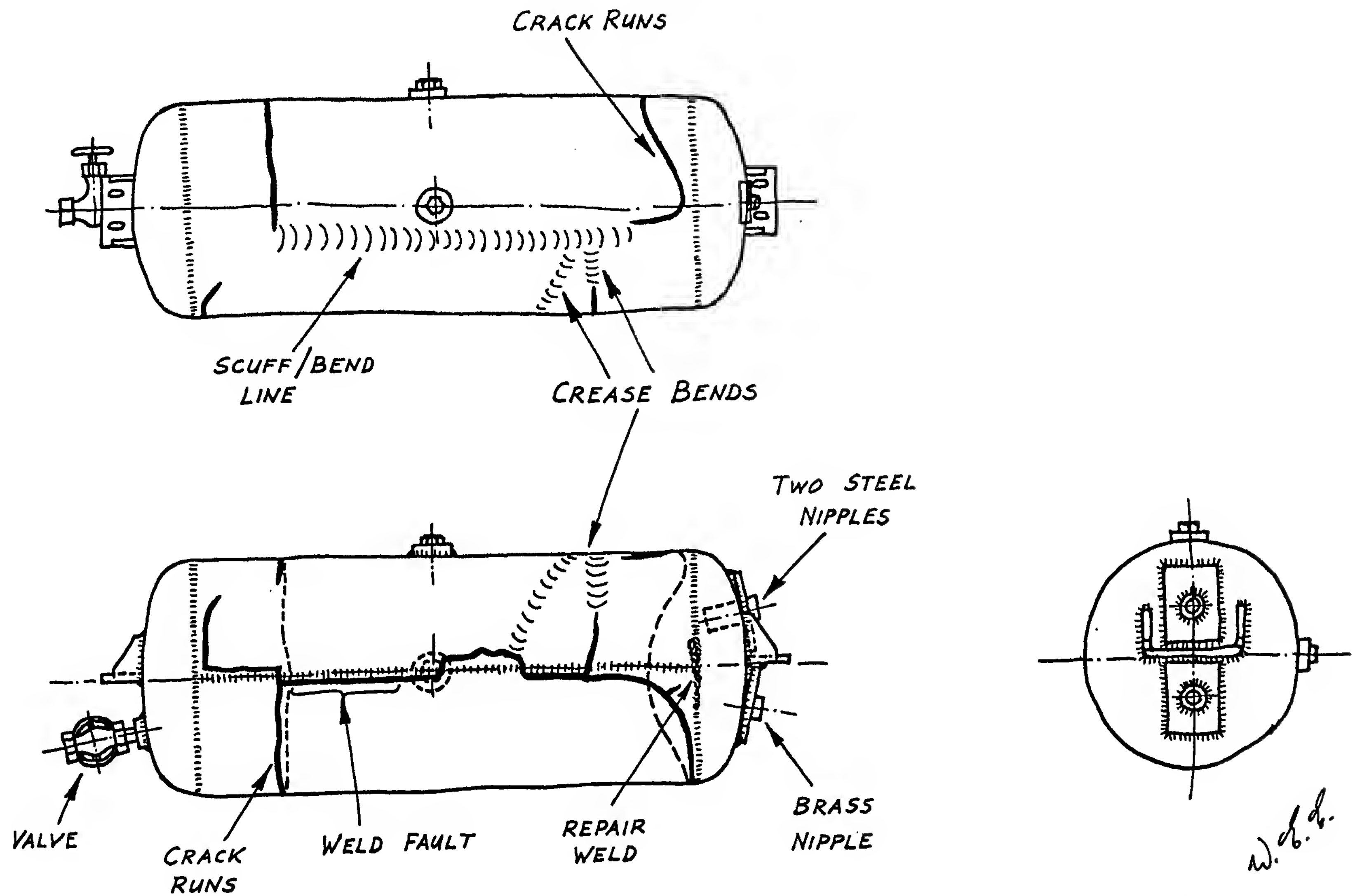

Exhibit 2 - INTERMEDIATE AIR RECEIVER, E.R.C.B. - FRACTURE

fig. 1 - Fractured Air Receiver, outer surface of body.

fig. 2 - Fractured Air Receiver, inner surface of body.

fig. 3 - Fractured Air Receiver.

fig. 4 - Edge of fracture along Longitudinal Weld Seam.

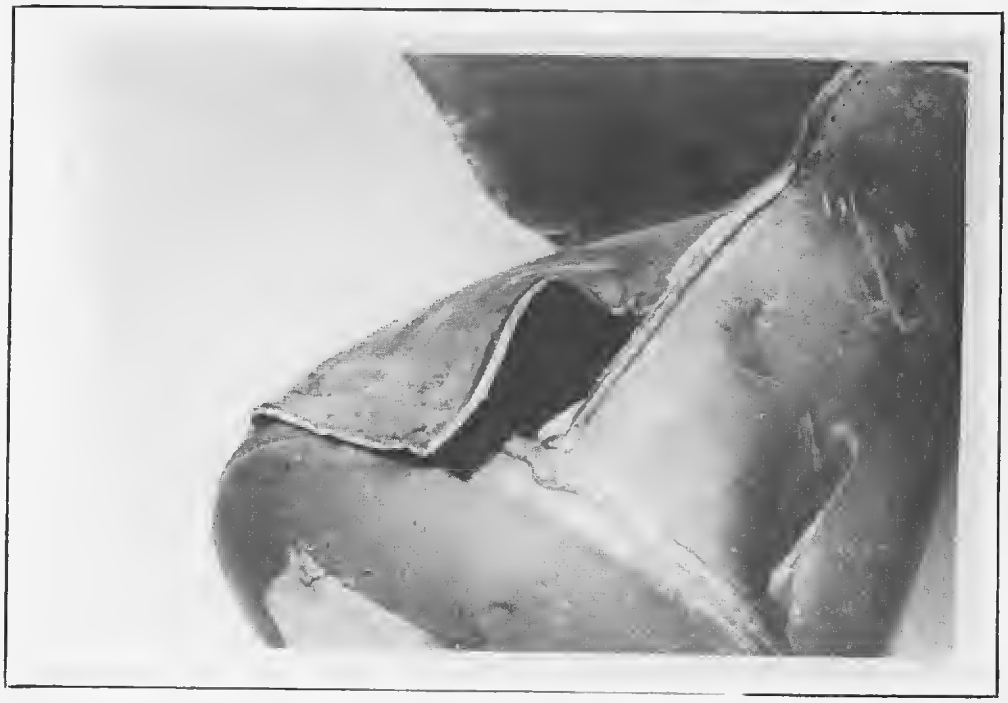

fig. 5 - Fracture at Unmodified Head.

fig. 6 - Fracture at Modified Head.

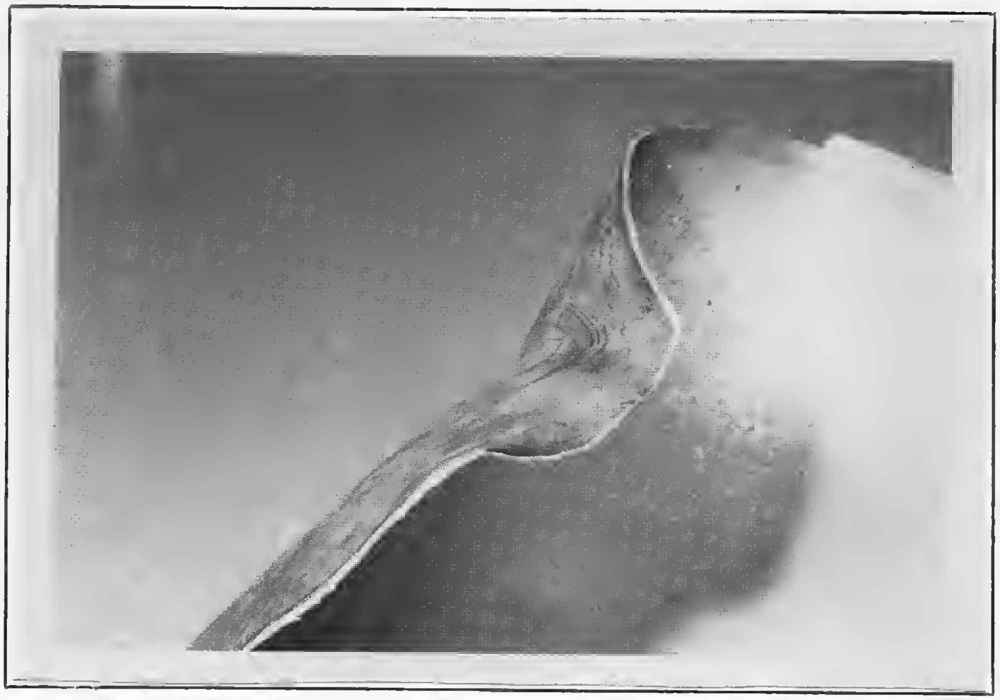

fig. 7 - Body Plate at Modified Head; note the deformed shape as fracture changes direction.

fig. 8 - Longitudinal Seam; note fracture in the heat-affected zone along most of the weld, and lack of weld penetration along inner edge.

fig. 9 - Longitudinal Seam, Weld Underside; note good weld penetration at left, with fracture in the parent metal.

fig. 10 - Scuff Marks from Impact.

fig. 11 - Deformation due to Impact.

fig. 12 - Impact Location.

fig. 13 - Modified Head, outside view.

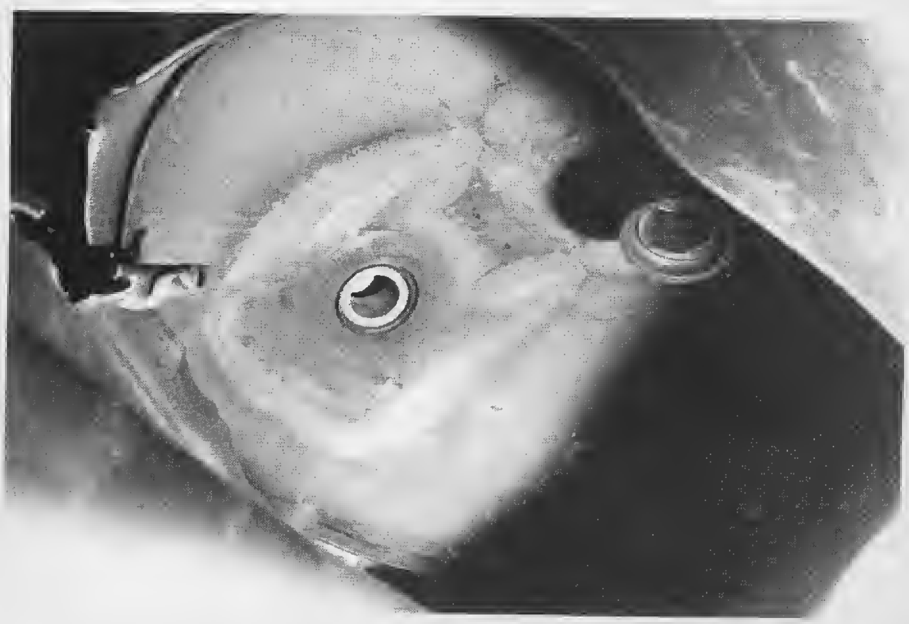

fig. 14 - Modified Head, inside view.

INTERMEDIATE AIR RECEIVER FRACTURE - PART B

At this stage, I built a model out of stiff white drawing paper, and marked on it the various features and viewing directions for figures of PART I. The development is sketched in exhibit 3.

I considered that the most important point to clear up was the detailed mode of fracture of various parts of the vessel. Fatigue was suspected, but where? And what were the effects of weld undercuts, and hand welds made to modify the vessel?

MAJOR SECTIONING

The modified head of the intermediate air receiver was cut along the center of the two entries, see figs. 15, 16 and 17. One half of this head was filed flat, and macro-etched in a 10% HNO_3 (Nitric acid in water) solution for 30 minutes, to reveal the major boundaries of weld-metal and other discontinuities. The short boss containing the brass screwed pipe end looked as if it was probably original equipment, a good weld was revealed around the outer edge.

The pipe containing two steel screwed pipe ends was apparently installed by the user. The weld to the vessel head was variable in quality, and showed severe undercutting and lack of melting close to the mounting bracket, where access to the weld by a hand-held electrode would be very restricted.

Both reinforcing plates on the modified head were appreciably above the head surface, resting on existing weld metal. The welds around the edges therefore had to bridge a gap of up to 1 mm (3/64 in.). External

appearance of these welds was uneven, with some burned-in undercuts into the reinforcing plates and into the head metal, and remains of slag on the weld. They were obviously made by hand-held electrodes. In section, the welds were of reasonably good appearance.

Further welds were laid onto the reinforcing plates around the boss and the inserted pipe. These welds showed greater variability, with some slag inclusions and some slag-filled holes leading into the gap between the head and the reinforcement.

The heating and cooling introduced during hand welding of the reinforcements caused the head to deform from its original smoothly rounded shape, the distortion being visible by naked eye on the inner surface of the head.

Fracture surfaces of the three screwed pipe ends remaining in the modified head led to some suspicions. The brass end in the boss was conical for part of its circumference, and radial for the rest. The outer steel end showed a conical fracture surface at about 45^{o} to the axis for most of its circumference. The inner steel end had an essentially radial fracture surface, with the exception of two short lengths approximately at the line of sectioning of this head, where the fracture was at about 30^{o} to the radial direction. Close-up views of these fracture surfaces are shown in figs. 18 and 19. The fracture surfaces were somewhat corroded. I could no longer see any useful features that might indicate the mode of fracture.

The inner of these two screwed pipe ends was apparently the remains of

a pipe extending internally to the other end of the receiver, intended to direct the air flow over the surface of the drying liquid. This extension pipe was not brought to me, it seems no-one looked for it in the loading machine.

DETAIL OBSERVATIONS

Sample sections were cut from various parts of the receiver, mounted in transparent cold-setting polyester resin, polished and etched for microscope observation in a 2% HNO_3 (Nitric acid in absolute alcohol) solution for 30 seconds. In each case, a part of the sample was mounted normal to the interesting direction, and another part parallel to it, in order to be able to check on differences in undisturbed grain structure that may appear because of the manufacturing process (rolling) used to make the sheet steel. I detected no appreciable effect of rolling direction on grain structure.

Sample 1 (fig. 20) was taken from about the middle of the vessel, at the free edge of the rupture (see exhibit 3). It shows the 45° slope of the rupture surface and the thinning behind it. The grain structure under microscopic observation shows a distinct stretching of individual grains as the fracture surface is approached. Failure was in a shear mode, typical of a ductile fracture under relatively low rate of stress application, with little constraint by stress concentration effects.

Sample 2 (fig. 21) shows the fracture leading from the longitudinal weld. The step resulting from incomplete penetration of the weld at this point can be clearly seen. The fracture surface is along the

heat affected zone of the weld region, starting almost parallel to the parent metal surface, and curving outwards to that surface. The weld shows a coarser, dendritic structure, as would be expected from a good weld that had not received an annealing or normalizing heat treatment.

Sample 3 (fig. 22) was taken from the longitudinal weld at a point of good weld penetration. The fracture here is remote from the weld, and shows similar stretching to sample 1.

Sample 4 (fig. 23) shows the machine-welded section of the head-to-body weld at the modified head. The weld is good, with adequate melting into the parent metal of the head. Sample 5 (fig. 24) is taken from the repaired portion of the head weld. It reveals that the initial weld was made over a fairly large gap, probably about 0.5 mm (0.020 in.), the overlaid hand weld is of coarse grain structure, with somewhat irregular dendrite distribution. This weld could be classed as of medium quality; I suspect that it was a repair weld made by the vessel manufacturer when a leak was detected under test.

The three screwed pipe ends were removed from one half of the cut modified head, and mounted in resin. The brass pipe end showed stretching of the grain towards the fracture surface, indicating a ductile failure. The outer of the two steel pipe ends showed similar stretching of grains, and the usual 45° direction of the fracture surface; it too was ductile.

The inner screwed pipe end showed a fracture surface that varied in

angle from 90° to about 60° to the axis, the lower angle portions being shorter and opposite one another approximately in the plane of cutting of the head. The etched surface revealed that the grain boundaries were approximately in their original positions; I saw no evidence of stretching. This is more typical of a fatigue fracture. No fatigue striations were detectable on the fracture surface by unaided eye, but moderate magnification by eye lens showed, in spite of the existing corrosion, a coarse-grained surface with some shallow lines about at right angles to the cutting plane, which I judged to be the fatigue striations.

I concluded that the vessel was probably mounted with its axis horizontal on upright supports, thus creating a long shallow pool of the drying liquid. The bolts through the vessel's mounting lugs were horizontal. The pipe that I presume extended inwards along the length of the vessel was cantilevered from the screw thread of the inserted short tube. It was obviously screwed tight before the tube was welded into the head. Service vibrations transmitted in the vehicle could excite this pipe into natural vibrations, and eventually lead to a fatigue fracture. Subsequent use of the machine would then vibrate the loose pipe inside the vessel, incidentally causing a rattling noise that might have lead an operator to think that the vessel mountings were loose.

FRACTURE CONDITIONS

An assumption as voiced to me by Mr. Smith at a later meeting, that the operator had by mistake filled ether into the air receiver may be

justified, but an alcohol charge could, in my opinion, also be responsible for the failure. Ethyl alcohol (pure) has a melting point of -114.6°C (-174.2°F), and a boiling point of 78.5°C (172.9°F). At any intermediate temperature, alcohol vapour rises from the liquid at a rate determined by temperature and the concentration of alcohol in the surrounding air. A mixture of alcohol in air is flammable, when the alcohol content is between 3.3% and 19% by volume of vapour. The flash point of ethyl alcohol is 12.8°C (55°F), at any temperature above this value, a spark could initiate combustion.

From the evidence gathered so far, I constructed a sequence of events to explain this failure as follows: alcohol was filled into the vessel by the operator; shortly thereafter the operator took (or was forced to take) a break, leaving some liquid in the vessel; during the rest period the alcohol concentration in the vessel's air space increased to within the flammability limits; on restarting the machine, the fractured pipe rattled in the vessel, hit the side above the liquid line with sufficient force to strike a spark, and initiated the burning of the mixture. A rapid temperature and pressure rise followed, which started the rupture close to the main body weld seam at a point of incomplete penetration. Ejection of the combustion gases through the fracture caused a rocket effect, sufficient to tear the vessel from its mounting, and propel it against a structural member whilst also tearing the connecting piping.

CONCLUSIONS

The use of alcohol, or any other easily combustible substance, should be avoided for the purposes of prevention of freezing at air exhausts.

Alternative methods are available; one of these is the use of a solid dessicant (silica gel, or anhydrous indicating calcium sulphate) in a filter cartridge immediately before the compressor. Such dessicant materials can be regenerated, preferably outside the machine. This can be accomplished with low down-times by providing a replacement cartridge to the operator.

Pressure vessels of this type should not be modified, except under the supervision of a competent professional engineer, who should insist on full pressure testing after modification. This may in fact have been done, but I felt it important to stress the point to ERCB and the mining companies. Any insert tubes should be supported at two points, i.e. at both heads of the vessel, to minimize the danger of large-amplitude vibrations and consequent fatigue fracture. Piping leading to such a pressure vessel should be adequately supported close to the vessel entry. Head reinforcement should not be necessary if modifications and mountings are carefully designed.

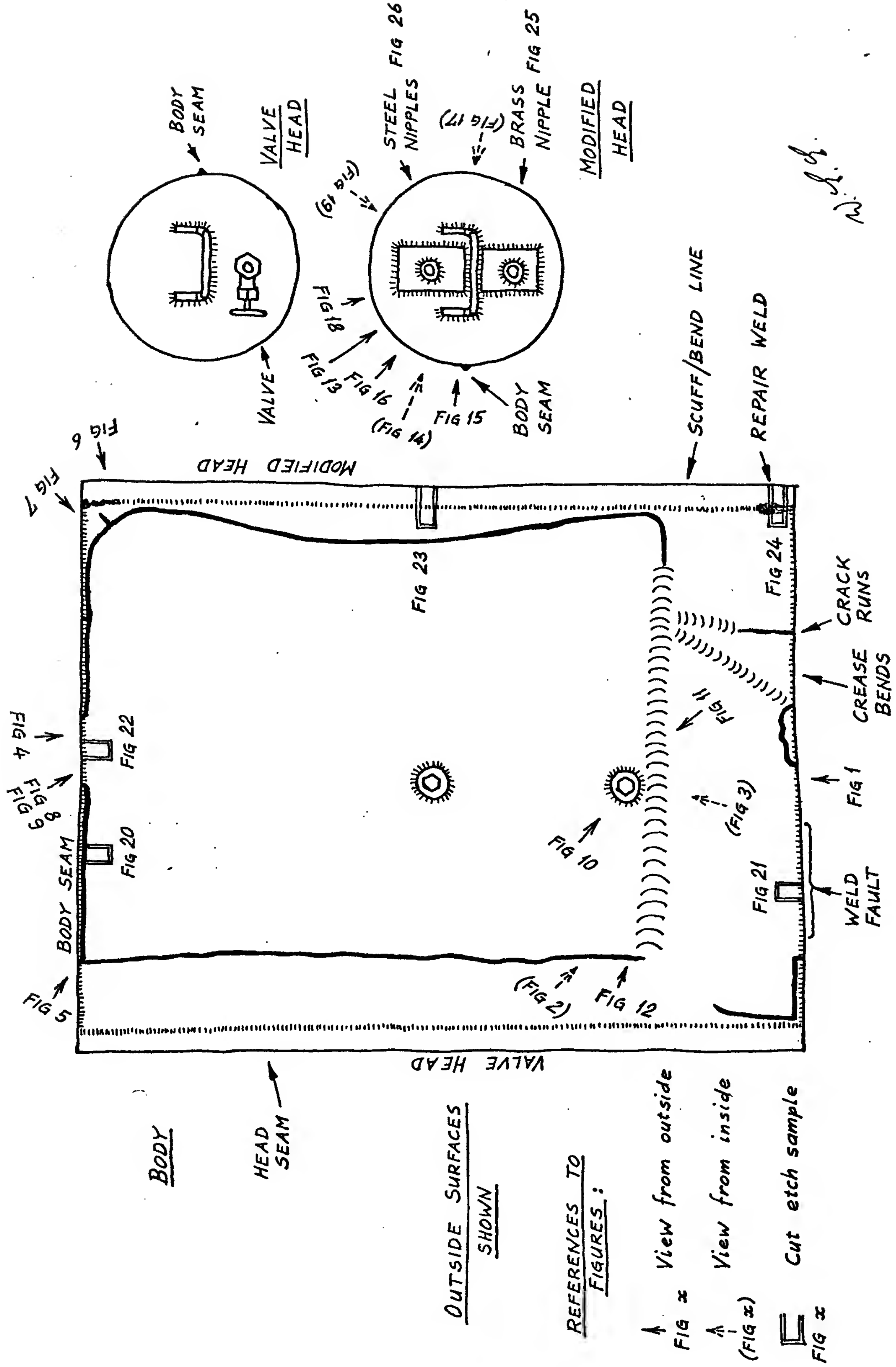

Exhibit 3 - INTERMEDIATE AIR RECEIVER, E.R.C.B. - DEVELOPMENT

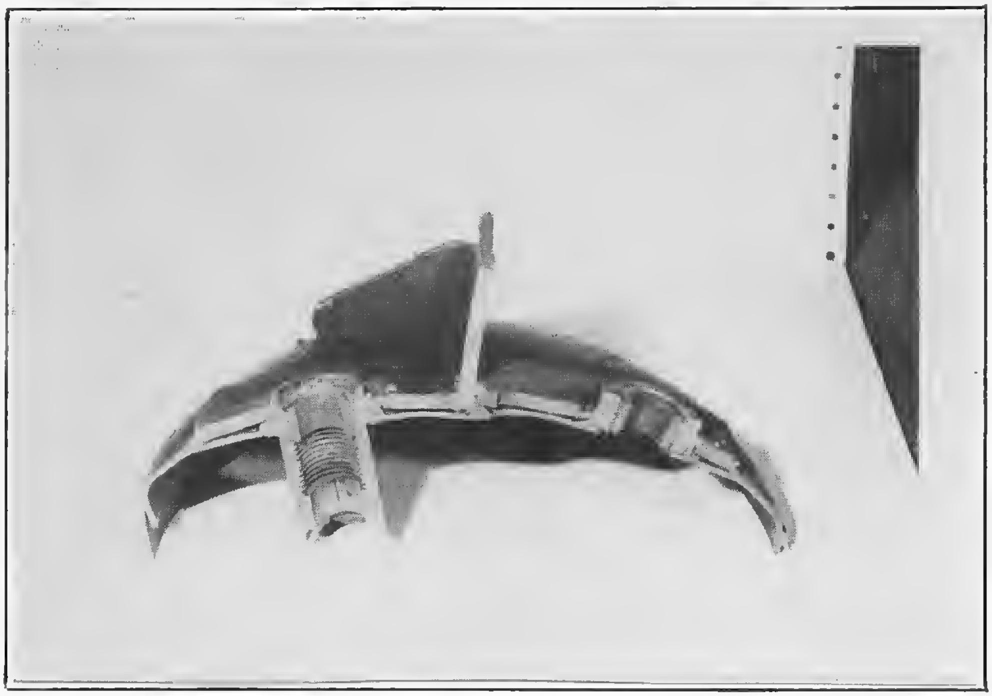

fig. 15 - Modified Head, section prepared for macro-etching.

fig. 16 - Modified Head, section.

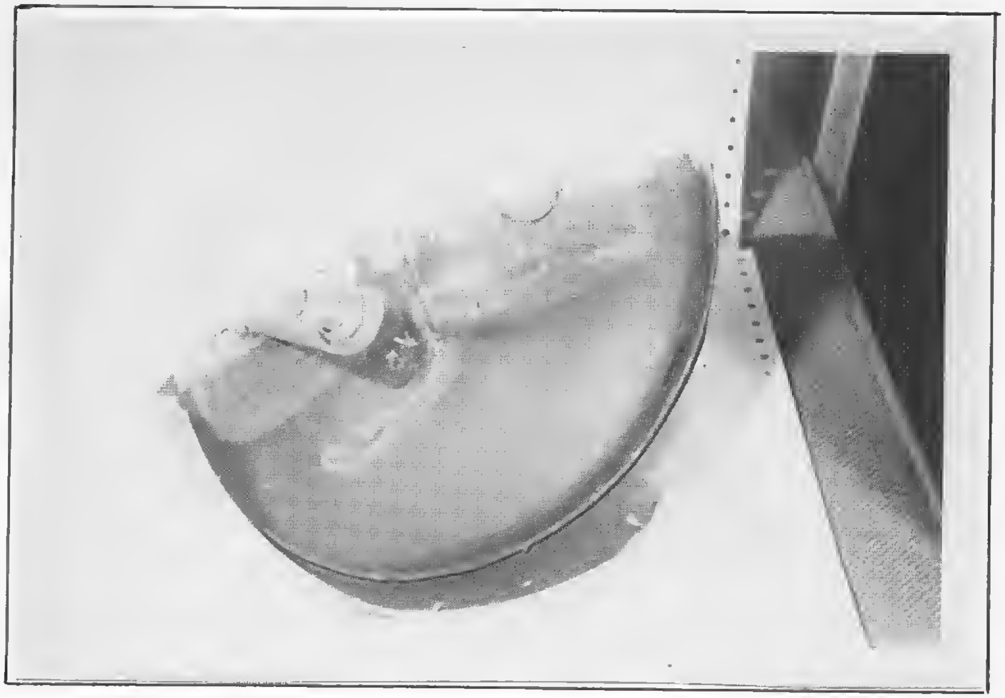

fig. 17 - Modified Head, inner surface.

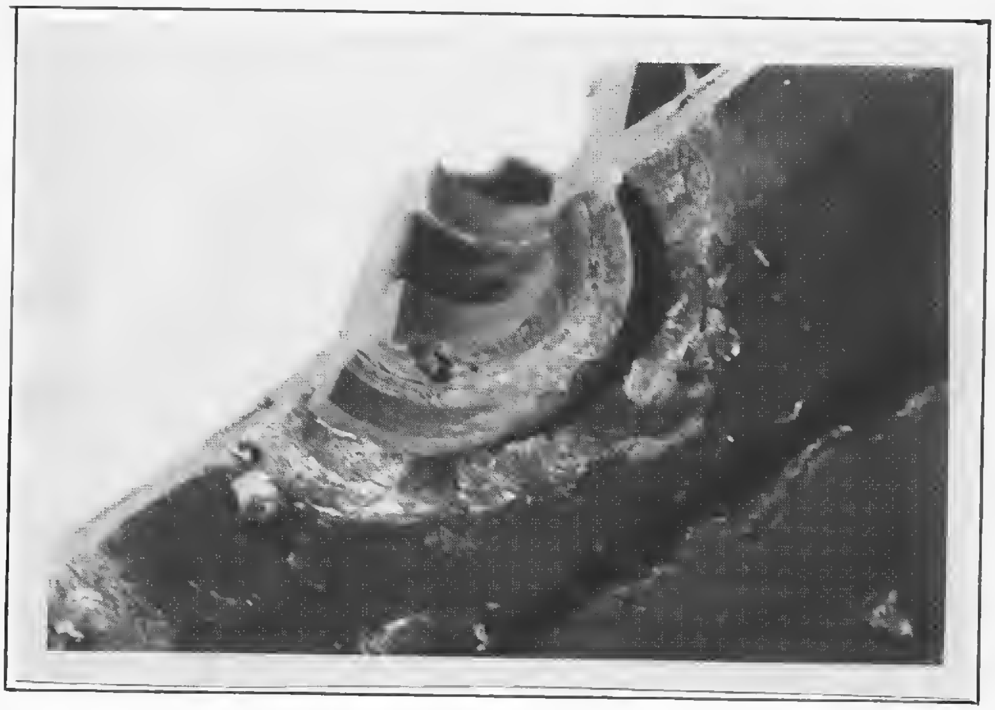

fig. 18 - Pipe Entry, outer end.

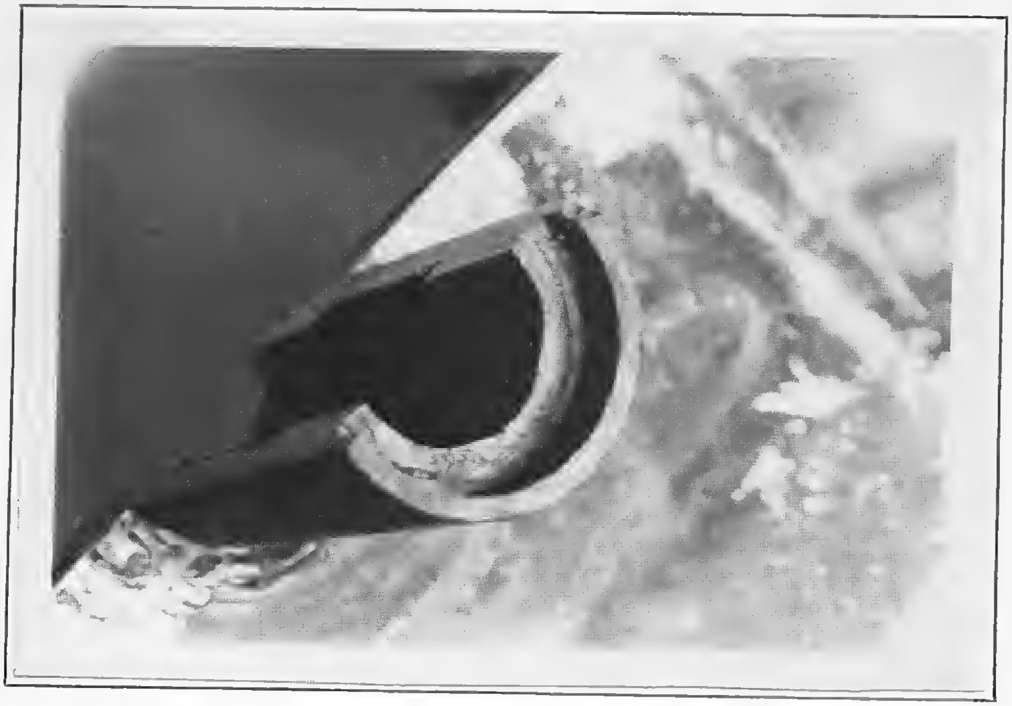

fig. 19 - Pipe Entry, inner end.

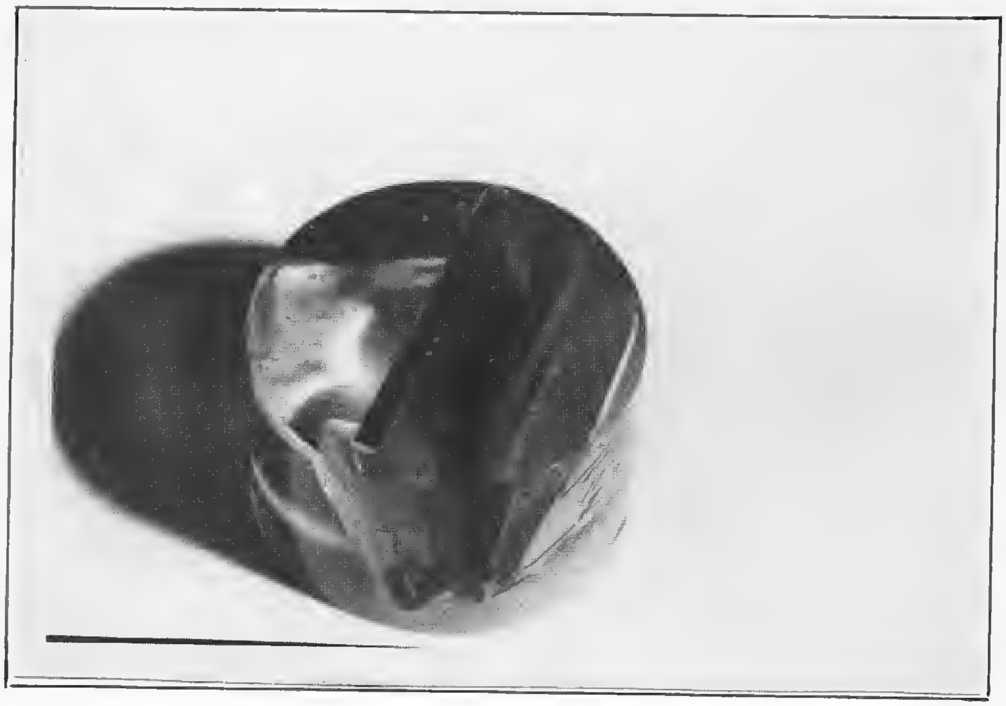

fig. 20 - Fracture Edge; note thinning (on right-hand sample towards front) and slope of fracture edge.

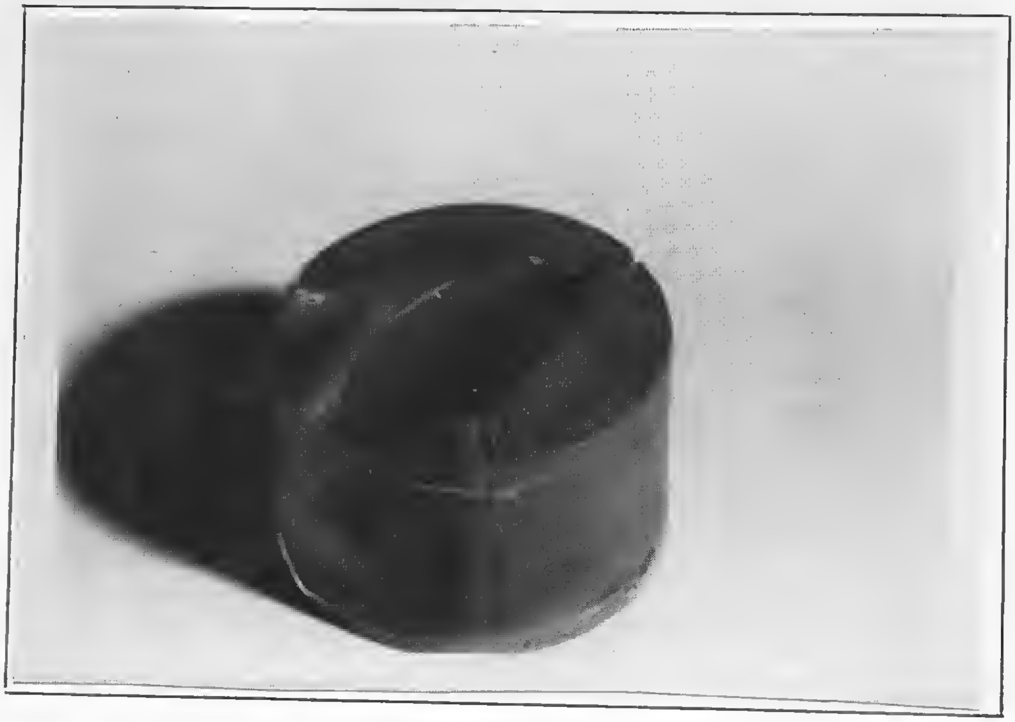

fig. 21 - Longitudinal Weld Seam, incomplete penetration; note step at front of right-hand sample, opposite the raised weld bead.

fig. 22 - Longitudinal Weld, complete penetration; fracture in parent metal, thinned by stretching as in fig. 20.

fig. 23 - Head Weld Seam, original weld metal (middle sample), head to left, body to upper right.

fig. 24 - Head Weld Seam, repair weld by hand (top sample), head to right, body to upper left.

INSTRUCTOR'S NOTES TO PART A

INTERMEDIATE AIR RECEIVER FRACTURE

Useful exercises at this stage include:

a) Speculate on air circuit features relevant to this case, mounting method, and geometry for the vessel. Construct a stiff paper model of the vessel, and compare the ruptured version with the photographs.

b) Calculate the conditions in various parts of the air circuit during operation (external air temperature and relative humidity, compression temperature, relative humidity in the cooled compressed air, exhaust conditions), and determine limits for possible ice formation at the exhaust ports. At this stage, I have mentioned to students that in Alberta open-cast mining operations the working temperatures may drop to $-40^{\circ}C$ on occasions, BUT calculations show that conditions above freezing point are more likely to cause exhaust freezing.

c) Determine properties of alcohol and ether, from handbooks, especially concerning combustion, water absorption and freezing point, and speculate about the probable effectiveness of the drying system as installed.

d) Estimate the pressure at which such a vessel would burst, assuming a medium carbon steel, cold rolled, and suitable welding efficiencies. Why were other parts of the air circuit NOT damaged?

e) Plan additional investigations needed to determine failure modes at various key points of the vessel.

f) Speculate on possible causes for the failure and make recommendations for prevention of similar failures.

g) Estimate the available force to "rocket" the vessel. Is such a force large enough to shear the bolts and the external piping? What effects do you expect from the inertia of rupturing and moving body plates?